NACA RM E56D10a

NACA

RESEARCH MEMORANDUM

ESTIMATION OF SPECIFIC SURFACE OF FINELY DIVIDED MAGNESIUM

By Murray L. Pinns

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
August 20, 1956
Declassified October 14, 1957

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

ESTIMATION OF SPECIFIC SURFACE OF FINELY DIVIDED MAGNESIUM

By Murray L. Pinns

SUMMARY

A preliminary investigation into the use of the adsorption of cetyl alcohol from hydrocarbon solution as a means of estimating the specific surface of finely divided magnesium indicated that the method may be satisfactory. Magnesium-hydrocarbon slurries containing 49 or 50 percent magnesium and 0 to 5 percent cetyl alcohol were prepared from two batches of atomized magnesium and two batches of vapor-process magnesium. The equilibrium concentration of cetyl alcohol in the supernatant liquid from each slurry was determined by measuring the interfacial tension between the liquid and water, and from this the quantity of cetyl alcohol adsorbed per unit weight of magnesium was calculated. These quantities approached limiting values for the atomized magnesium, but no limit was observed for the vapor-process magnesium. The specific surfaces and volume-surface average particle diameters of the atomized magnesium were calculated from the molecular cross section of cetyl alcohol, the Langmuir equation, and an assumed ratio of surface to volume of the magnesium particles.

Specific surfaces and average particle sizes were also calculated from the adsorption of cetyl alcohol at minimums in the plots of Brookfield apparent viscosity or yield value against concentration of cetyl alcohol in the slurry. These results are consistent with those from the previous calculations, and the method is applicable to all four batches of magnesium.

For the atomized magnesium, specific surfaces of about 3 and 7 square meters per gram were estimated; for the vapor-process magnesium, about 10 and 20 square meters per gram (approximately 1 to 2 acres per lb). The corresponding average particle diameters, about 1.2, 0.5, 0.4, and 0.2 microns, respectively, agree within a factor of 2 or better with particle-size estimates obtained by air permeability or electron microscopy.

INTRODUCTION

Investigations carried out at the NACA Lewis laboratory have shown that slurry fuels consisting of finely divided magnesium dispersed in a

hydrocarbon fuel potentially offer wider operating limits and greater thrust in jet engines than do the hydrocarbons alone (ref. 1). It has also been indicated that this advantage increases as the magnesium becomes more finely divided (ref. 1). This behavior suggests a possible correlation between performance and the specific surface (surface area per unit weight) of the magnesium. The present report describes a preliminary investigation of a method that may be suitable for estimating the specific surface of very finely divided magnesium. Such an estimation would also be an aid in the control of production of vapor-process magnesium and the preparation of magnesium-slurry fuels.

The method investigated involves the determination of the quantity of cetyl alcohol adsorbed from hydrocarbon solution by the magnesium. The use of the measurement of adsorption from a liquid phase to determine specific surface is reported in reference 2 and elsewhere, although gas-phase adsorption is usually preferred because of the smaller molecules of adsorbate. However, for very finely divided magnesium, especially vapor-process magnesium (ref. 3), which is available only when immersed in liquid hydrocarbon, satisfactory adsorption from the gas phase is exceedingly difficult, if not impossible.

Interfacial tension measurements were used to determine the adsorption of cetyl alcohol. Somewhat similar techniques have been used by other investigators. In reference 4, the adsorption of fatty acids from hydrocarbon oil onto steel balls was followed by plotting against time the interfacial tension between the solution and water. In reference 5, the adsorption of detergents from water onto sand was determined from the surface tension of the solution. In this investigation, slurries of magnesium suspended in hydrocarbon solutions of cetyl alcohol were prepared with each of two batches of atomized magnesium and two batches of vapor-process magnesium. The specific surface of the magnesium from each batch was calculated by means of the Langmuir adsorption equation when possible, and from a correlation between adsorption and some rheological properties of the slurries. The average particle diameters that were calculated from the specific surfaces were compared with electron-microscope observations.

METHOD

Cetyl alcohol has been demonstrated to be a surface-active additive that makes concentrated magnesium-hydrocarbon slurries more fluid (refs. 6 and 7). Extensive experimental evidence exists that surface activity is the result of oriented adsorption of the surface-active additive at an interface (in this case, the magnesium-hydrocarbon interface) (ref. 8). Adsorption from a liquid solution causes depletion of the additive from the bulk of the liquid; the extent of this depletion is therefore a measure of the quantity of additive adsorbed. Experiments have indicated that molecules of cetyl alcohol adsorbed on a water surface can be crowded

into a monomolecular, close-packed, oriented film in which each molecule, on the average, occupies a fixed area on the surface of the water (refs. 9 and 10). If it is assumed that a magnesium (or magnesium oxide) surface will adsorb as many molecules of cetyl alcohol per unit surface area as does water, the surface area per unit weight of magnesium can be calculated from the depletion of cetyl alcohol from the solution. This assumption implies that the magnesium surface offers to the cetyl alcohol as many activated, accessible sites for adsorption per unit surface as does a water surface.

The interfacial tension between water and hydrocarbon solutions of various nonionic surface-active additives is known to vary continuously with concentration at low concentrations of additive (ref. 11). Tests at the Lewis laboratory have shown that this behavior is true of cetyl alcohol at concentrations up to about 5 percent. It appears, therefore, that it should be possible to determine from the interfacial tension of the solution against water the concentration of cetyl alcohol remaining after adsorption has reached equilibrium, as long as the concentration does not exceed about 5 percent. From the difference between the initial and equilibrium concentrations, the quantity of cetyl alcohol adsorbed was calculated; and, from this quantity and the surface area per molecule (determined from films on water), the specific surface of the magnesium was calculated.

Calculation of Cetyl-Alcohol Adsorption from Langmuir Equation

By combining various forms of the Langmuir equation as given in reference 12, the Langmuir adsorption equation can be put into the form

$$\frac{c}{x} = \frac{1}{kx_s} + \frac{c}{x_s} \tag{1}$$

where

c concentration of cetyl alcohol in hydrocarbon in equilibrium with magnesium particles

x weight of cetyl alcohol adsorbed per unit weight of magnesium

k constant

x_s weight of cetyl alcohol required to saturate the adsorbing surface of a unit weight of magnesium

Therefore, if the adsorption of cetyl alcohol on magnesium follows the Langmuir equation, a plot of c/x against c is linear, and the

reciprocal of its slope is x_s, the weight of cetyl alcohol required to saturate the surface of a unit weight of magnesium. If this quantity represents a monomolecular layer as closely packed as it is on water in a film balance, then the specific surface and the average particle diameter of the magnesium can be calculated from the reciprocal of the slope of the Langmuir plot by the use of equations (2) and (3), which follow.

Calculation of Specific Surface from Weight of Adsorbed Cetyl Alcohol

The specific surfaces reported were calculated from the equation

$$S = \frac{x_s NA}{M} \tag{2}$$

where

S specific surface

N Avogadro's number

A area occupied by each molecule of cetyl alcohol

M molecular weight of cetyl alcohol

The area occupied by a molecule of cetyl alcohol under the least pressure that will produce a close-packed, monomolecular film is 20.5 square Angstrom units (average of values from refs. 9, 10, and 13).

Calculation of Particle Diameter from Specific Surface

The calculated specific surfaces were converted to mean volume-surface diameters by use of the equation

$$d_3 = \frac{6}{\rho S} \tag{3}$$

where

d_3 mean volume-surface diameter

ρ density of magnesium

Equation (3) is commonly used for powdered materials where the particle shape is not highly asymmetric (ref. 14).

MATERIALS

Magnesium

The four batches of magnesium used were designated C, D, FP-1, and FP-3, and are described in table I. Batches C and D were prepared commercially by atomizing molten magnesium in a helium atmosphere and collecting the finest fraction. Magnesium C was used in part of the work reported in reference 2, and was designated as such therein. While batches C and D were both received as dry powders, only C was handled in that condition. In order to decrease the fire hazard, D was wetted in its shipping drum with sufficient decane to form a concentrated paste, as indicated in table I.

Batches FP-1 and FP-3 were prepared at the Lewis laboratory by the vaporization process described in reference 8. Magnesium FP-1 was used and designated as such in the work reported in reference 3. Both batches of vapor-process magnesium were supplied for the present investigation as pastes in hydrocarbon, as described in table I.

Hydrocarbons

Magnesium batches C and D were made into slurries by the addition of suitable quantities of purified n-decane, the properties of which are listed in table II. Magnesium batches FP-1 and FP-3 were made into slurries by the addition of more of the same hydrocarbon that was present in the paste. The hydrocarbon used with FP-1 was JP-1 fuel (MIL-F-5616), while that used with FP-3 was JP-5 fuel (MIL-F-5624C) plus 10 percent fuel oil.

Cetyl Alcohol

Three batches of National Formulary grade cetyl alcohol were used; they were designated as batches 1, 2, and 3. Batch 1 was used with magnesium C and magnesium FP-1. Batch 2 was used with magnesium FP-3, and batch 3 with magnesium D. The capillary-tube melting points of the cetyl alcohol and the calculated purities based on a reported freezing point of 49.2° C (ref. 15) are given in the following table:

Batch	Melting point, °C	Calculated purity, mole percent
1	47.7 to 48.2	92
2	47.3 to 47.8	90
3	47.8 to 48.3	93

Since cetyl alcohol is commonly prepared from fats, the impurities are probably mainly homologous alcohols with two to four methylene groups more or less per molecule than cetyl alcohol. Such molecules are similar in chemical behavior and occupy similar areas when adsorbed; therefore, the effective purity of the cetyl alcohol is greater than indicated by the calculated purity. The molecular weight of the 92- to 94-percent-pure cetyl alcohol was taken to be 242, the same as that of pure cetyl alcohol, because the alcohols of higher molecular weight constituting the impurity probably compensated for those of lower molecular weight.

PROCEDURE

After the slurries were mixed, they were aged; and then their Brookfield apparent viscosities, plastic viscosities, and yield values were determined. Each slurry was centrifuged and the interfacial tension between the supernatant liquid and water was measured. The concentration of cetyl alcohol corresponding to the interfacial tension was found from a calibration curve and was used to calculate the weight of cetyl alcohol remaining in the liquid. The difference between this weight and the initial weight of cetyl alcohol in the slurry was taken as the weight of cetyl alcohol adsorbed and was used in subsequent calculations.

Preparation of Slurries

Batches of slurry weighing 400 or 800 grams were prepared in new, clean, pint or quart paint cans. The cetyl alcohol was weighed into each can to the nearest 0.01 gram (or 0.001 g for the smaller quantities used with magnesium D and magnesium FP-3), and part of the hydrocarbon was added. The can was warmed until the alcohol was dissolved, and the remainder of the hydrocarbon was weighed into the can. A sufficient quantity of magnesium to make a 50-percent slurry (49 percent in the case of magnesium FP-1) was added last. Slurries of magnesium C were mixed with a motor-driven stirrer while being heated to 60° to 71° C (140° to 160° F) on a hot plate, and then any evaporated decane was replaced. Slurries of the other batches of magnesium were shaken on a commercial paint conditioner for 30 minutes. All the data reported were obtained after the slurries were aged for 30 to 60 days at room temperature.

Rheological Measurements

Brookfield apparent viscosity. - The Brookfield apparent viscosity, which is an apparent viscosity at a single, low rate of shear, was determined at 28° to 31° C (82° to 88° F) with a model LVF Brookfield Synchrolectric viscometer. Spindle 3 at 12 rpm (estimated rate of shear, 10

sec^{-1}) was used for apparent viscosities below 10,000 centipoises, and spindle 4 (estimated rate of shear 0.5 sec^{-1}) was used for higher apparent viscosities.

The measurements were made in the same cans in which the slurries were prepared. The cans of slurry were first shaken on a paint conditioner for 10 minutes (slurries of magnesium C were mixed with a motor-driven stirrer), the viscometer spindle was then immersed to the mark, and the reading was taken after the spindle had rotated for 30 seconds. Duplicate determinations agreed within 10 percent of the mean.

Flow curves, plastic viscosity, and yield value. - Flow curves for slurries containing magnesium D or magnesium FP-3 were obtained with the automatic concentric-cylinder rotational viscometer described in reference 16. The flow curve produced by this recording viscometer is a plot of rate of rotation of the cup against torque on the stationary bob. When a flow curve had a relatively long linear portion, the linear portion was extrapolated to the torque axis. The plastic viscosity of the slurry was calculated from the slope of the straight line, and the yield value was calculated from the torque intercept.

A new portion of thoroughly mixed slurry was taken for each flow curve for which data were reported. Determinations of the plastic viscosity and yield value of two or more new portions of the same slurry run on the same day agreed within 10 percent of the mean.

Interfacial Tension and Adsorption

Separation of supernatant liquids from magnesium. - All the slurries were centrifuged at 1750 rpm (approximately 500 times the force of gravity) for 2 to 3 hours. The supernatant liquids from slurries of magnesium FP-1 were further centrifuged at 29,000 rpm (maximum force approximately 100,000 times the force of gravity) for 2 hours.

Measurement of interfacial tension. - Interfacial tension was measured with a Cenco-du Noüy interfacial ring tensiometer at room temperature (28° to 30° C). The accuracy of the instrument was checked by measuring the surface tension of water prior to each set of interfacial-tension measurements. The platinum ring was 6 centimeters in circumference, and the measurements were made in 10-centimeter Petri dishes. Precautions were taken to minimize disturbances, contamination, and other sources of error.

The following procedure was used: A Petri dish containing approximately 25 milliliters of freshly boiled distilled water was set on the

tensiometer platform. The platform was raised until the water surface almost touched the ring. The ring was rotated in its ball-joint mounting until it was parallel with its reflection in the water. The platform was raised further until the water surface just touched the ring. About 50 milliliters of the cetyl alcohol - hydrocarbon solution was then poured onto the water surface in such a way as not to disturb the ring or cause any visible agitation of the water. For supernatant liquids from magnesium batches D, FP-1, and FP-3, the usual procedure of measuring interfacial tension by lowering the interface while applying an upward pull to the ring was begun 5 minutes ± 1 second after the addition of the cetyl alcohol solution began. For supernatant liquids from slurries of magnesium C, the measurement was begun several seconds after all the liquid had been poured into the dish. The corrected interfacial tension, which is the reported value, was obtained by applying a ring correction (ref. 17) to the instrument reading.

Duplicate or triplicate measurements were made on the supernatant liquid from a slurry whenever sufficient liquid was available. A new 50-milliliter portion of liquid was required for each measurement. Only single determinations could be made on the liquids from slurries of magnesium FP-1 or magnesium C. Duplicate measurements always agreed within 1 dyne per centimeter, and usually within 0.3 dyne per centimeter.

Preparation and use of calibration curves. - Standard solutions of the three batches of cetyl alcohol were prepared with the hydrocarbons that were used in making the slurries. The standard solutions contained approximately 5 percent cetyl alcohol, and a series of lower concentrations was obtained by diluting aliquots with additional hydrocarbon. Duplicate or triplicate measurements of the interfacial tension between each solution and water were made by the same procedure used for the corresponding supernatant liquid. A calibration curve of corrected interfacial tension against concentration was plotted for each cetyl alcohol - hydrocarbon combination. Figure 1 is the calibration curve for decane containing cetyl alcohol from batch 3. The other calibration curves differed only slightly from this one.

RESULTS AND DISCUSSION

By use of the procedures previously described, the interfacial tension, quantity of cetyl alcohol adsorbed, and rheological properties were determined for each slurry (table III). From these data, adsorption isotherms (fig. 2), Langmuir plots (fig. 3), and Brookfield viscosity-concentration and yield-value - concentration curves (fig. 4) were prepared. The specific surface and mean volume-surface particle diameter of the magnesium from each batch were calculated by the use of figures 2 to 4. The calculated particle diameters were compared with those obtained with a Sub-Sieve Sizer, which probably also yields volume-surface

diameters, or with average diameters estimated visually by means of electron microscopy. The latter diameters may differ to some extent from volume-surface diameters.

On the basis that the effect of temperature on interfacial tension over the range of 26° to 30° C (79° to 86° F) is negligible, adsorption isotherms were obtained by plotting x, milligrams of cetyl alcohol adsorbed per gram of magnesium, against the initial concentration of cetyl alcohol in the slurry.

The adsorption isotherms plotted in figure 2 indicate that the adsorption of cetyl alcohol by the atomized magnesium, batches C and D, tended to reach a limiting value, whereas that by the vapor-process magnesium batches FP-1 and FP-3, did not do so in the concentration range examined. Possibly a limiting value would also have been reached for the vapor-process magnesium had the initial concentrations of cetyl alcohol been higher. If so, the equilibrium concentrations of cetyl alcohol would have been too high to be determined from interfacial-tension measurements.

Specific Surface and Particle Size from Langmuir Plots

The Langmuir plots for magnesium batches C and D are linear (fig. 3), as required by the Langmuir equation (eq. (1)) and as would be expected from the shape of the adsorption isotherms (figs. 2(a) and (b)). The specific surfaces calculated from equation (2) and the slopes of the plots in figures 3(a) and (b) are 2.8 and 7.8 square meters per gram for magnesium batches C and D, respectively. The corresponding average particle diameters, 1.2 and 0.44 micron (from eq. (3)), which are listed in table IV, agree reasonably well with the observed particle diameters.

Similar calculations could not be made for the two batches of vapor-process magnesium, FP-1 and FP-3. Not only were the Langmuir plots not linear, but the points were scattered. This behavior may be related to the appearance of the supernatant liquid that was obtained from the slurries by centrifuging at 1750 rpm. Slurries of atomized magnesium yielded clear liquids, whereas the slurries containing vapor-process magnesium yielded dark liquids at this speed (unless no cetyl alcohol was present) or even at 6000 rpm. When the dark liquids from the slurries of magnesium FP-1 were further centrifuged at 29,000 rpm for 2 hours, they became amber-colored and appeared to be transparent, but still had a pronounced Tyndall effect. The data for FP-1 were obtained from these amber liquids. The data for FP-3 were obtained from the dark liquids resulting from centrifuging only at 1750 rpm.

Specific Surface and Particle Size from Rheological Data

It has previously been reported for slurries of magnesium batches C or FP-1 that a plot of Brookfield apparent viscosity or yield value against concentration of cetyl alcohol seems to exhibit a minimum (refs. 6 and 7). These plots, based on data from references 6 and 7, are shown in figures 4(a) and (c). Slurries made with magnesium batches D or FP-3 seem to exhibit similar minimums (figs. 4(b) and (d)). Considering the probable experimental error in the rheological measurements, the Brookfield viscosity minimums were more pronounced for the slurries of atomized magnesium, while the yield-value minimums were more pronounced for the slurries of vapor-process magnesium. While the minimums are not deep and are therefore not of great practical significance in regard to the flow behavior of slurries, their consistent appearance suggests that the fundamental relation between adsorption and surface activity is involved. It therefore seemed possible that the minimums might be useful in estimating specific surface.

To test this possibility, x, the weight of cetyl alcohol adsorbed per gram magnesium, was taken from figure 2 at the same initial concentration of cetyl alcohol that produced the viscosity and yield-value minimums in figure 4. This weight of cetyl alcohol was substituted for x_s in equation (2). The specific surface and average particle diameter were calculated for each batch of magnesium by the use of equations (2) and (3), and the results are given in table IV.

For magnesium C, a specific surface of 3.0 square meters per gram and a particle diameter of 1.1 microns were calculated, in good agreement with the values calculated from the Langmuir plot; but the particle size is about 25 percent smaller than that given by the Sub-Sieve Sizer. A specific surface of 5.4 square meters per gram and a particle diameter of 0.63 micron were calculated for magnesium D. The particle diameter is about 45 percent larger than that calculated from the Langmuir plot, but within the range observed under the electron microscope. For magnesium FP-1, the calculated specific surface was 20 square meters per gram. The corresponding size, 0.17 micron, falls at the upper limit of the observed particle size range (table IV).

Since the Brookfield viscosity and yield-value minimums did not coincide for magnesium FP-3, the calculations based on these minimums cover a range, 7.9 to 11 square meters per gram and 0.30 to 0.42 micron. This particle size range is about 50 to 100 percent higher than the upper limit of the observed range. On the whole, however, there seems to be sufficient agreement between the observed and calculated values to support the supposition that the minimums may be useful for estimating particle size.

SUMMARY OF RESULTS

A preliminary investigation of the use of the adsorption of cetyl alcohol from hydrocarbon solution for the estimation of the specific surface of finely divided magnesium was made on two batches of atomized and two batches of vapor-process magnesium. The magnesium was made into slurries containing 49 or 50 percent magnesium and up to 5 percent cetyl alcohol. Adsorption determined by means of the interfacial tension between the supernatant liquids and water gave the following results:

1. Specific surfaces of 2.8 and 7.8 square meters per gram were calculated for the atomized magnesium by use of the Langmuir equation. Similar calculations could not be made for the vapor-process magnesium.

2. A correlation between adsorption and minimums in the plots of yield value or Brookfield apparent viscosity against cetyl alcohol concentration in the slurry gave 3.0 and 5.4 square meters per gram as the specific surface of the atomized magnesium. A similar correlation gave about 10 and 20 square meters per gram for the vapor-process magnesium.

3. Average particle diameters calculated from the estimated specific surfaces agreed within a factor of 2 or better with particle-size estimates obtained by electron microscopy or with a Sub-Sieve Sizer.

CONCLUDING REMARKS

Liquid-phase adsorption seems to offer promise as a means of estimating the specific surface of finely divided magnesium. Better results were obtained with atomized than with vapor-process magnesium; the data were less scattered, and the average particle diameters agreed a little better with the particle sizes observed under the electron microscope or with the Sub-Sieve Sizer. Considering the difficulty of properly determining particle diameters of such finely divided and nonuniform particles as occur in vapor-process magnesium, the discrepancies between the observed and calculated particle diameters are not extremely large. Some modifications in the procedure that are likely to improve the results with vapor-process magnesium are:

(1) Decreased magnesium concentration in the slurries to give more-fluid slurries with a higher permissible ratio of cetyl alcohol to magnesium.

(2) Constant agitation of the slurry during aging to achieve equilibrium adsorption more quickly.

(3) Improved centrifuging of the supernatant liquids.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, April 11, 1956

REFERENCES

1. Olson, Walter T., and Breitwieser, Roland: NACA Research on Slurry Fuels Through 1954. NACA RM E55B14, 1955.

2. Dallavalle, J. M., Orr, Clyde, Jr., and Blocker, H. G.: Research on Surface Properties of Fine Particles. Quarterly Rep. No. 3, State Eng. Exp. Station, Georgia Inst. Tech., Jan. 30, 1952. (Contract No. DA-36-039-sc-5411.)

3. Witzke, Walter R., Prok, George M., and Walsh, Thomas J.: A Preliminary Study of the Preparation of Slurry Fuels from Vaporized Magnesium. NACA RM E53K23, 1954.

4. Trillat, Jean-Jacques, et Brigonnet, Jean: Sur la détermination du nombre de molécules grasses adsorbées par un métal au cours de la lubrification. Compte Rendus, t. 228, May 16, 1949, pp. 1587-1588.

5. Hsiao, Lun, and Dunning, H. N.: A Comparative Study of Non-Ionic Detergent Adsorption by Radiotracer, Spectrophotometric, and Surface Tension Methods. Jour. Phys. Chem., vol. 59, no. 4, Apr. 1955, pp. 362-366.

6. Pinns, Murray L.: Effect of Surface-Active Additives on Physical Behavior of 50-Percent Slurries of 1.5-Micron Magnesium in n-Decane. NACA RM E54K22a, 1955.

7. Pinns, Murray L.: Effect of Surface-Active Additives on Physical Properties of Slurries of Vapor-Process Magnesium. NACA RM E55H26, 1955.

8. Adam, Neil Kensington: The Physics and Chemistry of Surfaces. Second ed., Clarendon Press (Oxford), 1938.

9. Harkins, William D.: The Physical Chemistry of Surface Films. Reinhold Pub. Corp., 1952.

10. Langmuir, Irving: The Constitution and Fundamental Properties of Solids and Liquids. II - Liquids. Jour. Am. Chem. Soc., vol. XXXIX, no. 9, Sept. 1917, pp. 1848-1906.

11. Gros, Audrey T., and Feuge, R. O.: Modification of Vegetable Oils. X - Effect of Monoglycerides on the Interfacial Tension of Oil-Water Systems. Jour. Am. Oil Chemists' Soc., vol. 28, no. 1, Jan. 1951, pp. 1-4.

12. Cassidy, Harold Gomes: Adsorption and Chromatography. Vol. V of Technique of Organic Chemistry, Arnold Weissberger, ed., Interscience Pub., Inc., 1951, pp. 50-52; 70-72.

13. Adam, N. K.: The Properties and Molecular Structure of Thin Films. Pt. II - Condensed Films. Proc. Roy. Soc. (London), ser. A, vol. CI, no. A712, Aug. 1922, pp. 452-471.

14. Fischer, Earl K.: Colloidal Dispersions. John Wiley & Sons, Inc., 1950.

15. Smith, John Charles: Higher Aliphatic Compounds. Pt. I. - The Systems Ethyl Palmitate - Ethyl Stearate and Hexadecyl Alcohol-Octadecyl Alcohol. Jour. Chem. Soc. (London), pt. I, 1931, pp. 802-807.

16. Weltmann, Ruth N., and Kuhns, Perry W.: An Automatic Viscometer for Non-Newtonian Materials. NACA TN 3510, 1955.

17. Zuidema, H. H., and Waters, George W.: Ring Method for the Determination of Interfacial Tension. Ind. and Eng. Chem., Anal. ed., vol. 13, no. 5, May 15, 1941, pp. 312-313.

TABLE I. - PROPERTIES OF MAGNESIUM

	Magnesium			
	C[a]	D	FP-1[b]	FP-3
Method of preparation	Atomization	Atomization	Vapor-process	Vapor-process
Hydrocarbon used to form paste	None (dry powder)	Decane	JP-1 fuel	JP-5 fuel plus 10% fuel oil
Solids content, percent	100	57	58	56
Assay, percent magnesium in solids[c]	92	94	87	90
Particle size, microns	[d]1.5	About 50% of particles <0.5 μ, about 40% 0.5 to 0.7 μ, remainder >0.7 μ[e]	Largely 0.06 to 0.2 μ. Occasional particles as large as 0.4 μ[f]	About 90% of particles <0.2 μ, remainder as large as 0.5 μ[e]
Density, g/cc	[g]1.76	(h)	[i]1.79	(j)

[a]Data taken from ref. 2.
[b]Data taken from ref. 3.
[c]By hydrogen evolution.
[d]By air permeability with Fisher Sub-Sieve Sizer.
[e]Estimated from examination under electron microscope at Lewis laboratory.
[f]Estimated by Dow Chemical Co., from electron micrographs.
[g]By volume displacement of decane.
[h]Assumed to be same as density of magnesium C.
[i]Average value, calculated from slurry densities in ref. 3.
[j]Assumed to be same as density of magnesium FP-1.

TABLE II. - PROPERTIES OF HYDROCARBONS

Property	Hydrocarbon		
	n-Decane	JP-1 fuel	JP-5 fuel plus 10 percent fuel oil
Melting point, °F	-21.4		
Boiling point at 760 mm, °F	345.3		
Distillation range, °F			
Initial boiling point		330	354
Percent evaporated			
5		343	378
10		355	389
20		363	401
30		373	413
40		380	425
50		390	436
60		401	446
70		413	457
80		432	471
90		460	493
95		488	512
Final boiling point		532	556
Residue, percent		1.0	1.0
Density at 86° F, g/cc	[a]0.7300	0.794	0.807
Aromatics (silica gel), percent by volume		15.9	11.9
Interfacial tension against water, dynes/cm	49.6 at 27° C (79° F)	42.9 at 28° C (82° F)	44.2 at 29° C (84° F)

[a]At 68° F.

TABLE III. - SUMMARY OF DATA

Interfacial tension of supernatant liquid, dynes/cm	Equilibrium concentration of cetyl alcohol in supernatant liquid, c, percent	Weight of cetyl alcohol in supernatant liquid, g		Weight of cetyl alcohol adsorbed, g	Weight of cetyl alcohol adsorbed per unit weight of magnesium, x, mg/g	$\frac{c}{x}$, $\frac{\%}{mg/g}$	Brookfield apparent viscosity, centipoises	Plastic viscosity, centipoises	Yield value, dynes/sq cm
		At equilibrium	Initially						
Magnesium C (800 g batches containing 400 g magnesium)[a]									
≈51	≈0	≈0	0.8	≈0.8	≈2	≈0	4480		
38.1	.42	1.68	4.00	2.32	5.80	.072	1630		
24.2	1.38	5.52	8.00	2.48	6.20	.223	2150		
13.3	3.45	13.80	16.00	2.20	5.50	.627	2480		
Magnesium D (400 g batches containing 200 g magnesium)									
48.3	0.07	0.14	1.00	0.86	4.3	0.0111	7080	27	400
43.2	.25	.50	2.00	1.50	7.5	.0333	2120	13	110
36.5	.45	.90	2.99	2.09	10.45	.0431	1680	13	100
32.8	.60	1.20	4.00	2.80	14.00	.0428	2050	10	110
22.4	1.67	3.34	6.00	2.66	13.30	.1315	2120	13	110
14.3	3.56	7.12	10.00	2.88	14.40	.247	2380	14	110
12.4	4.50	9.00	12.00	3.00	15.00	.300	2470	14	110
11.1	5.48	10.96	14.00	3.04	15.20	.360	2530	13	130
Magnesium FP-1 (400 g batches containing 197 g magnesium)[b]									
24.3	2.07	4.20	8.00	3.80	19.2	0.106	9480	40	450
22.3	2.40	4.87	12.00	7.13	36.2	.0658	8750	40	420
17.4	3.75	7.61	16.00	8.39	42.6	.0868	8820	37	420
15.3	4.95	10.09	20.00	9.91	50.3	.0966	9330	36	480
----	----	-----	24.00	----	----	-----	9450	40	510
Magnesium FP-3 (800 g batches containing 400 g magnesium)									
41.0	0	0	0	0	0	0	60,000	79	2440
29.8	.39	1.56	4.00	2.44	6.10	.0640	37,000	49	840
26.3	.71	2.84	6.00	3.16	7.90	.0898	26,000	40	620
24.1	1.16	4.64	8.00	3.36	8.40	.1380	9,120	35	510
23.4	1.42	5.68	10.00	4.32	10.80	.1315	8,100	30	440
21.8	2.05	8.20	12.00	3.80	9.50	.216	8,500	37	450
21.0	2.39	9.56	16.00	6.44	16.10	.1485	7,760	31	370
18.8	3.18	12.72	20.00	7.28	18.20	.197	7,690	32	410
16.8	3.90	15.60	24.00	8.40	21.00	.186	7,550	33	400
12.1	5.60	22.40	28.00	5.60	14.00	.400	7,950	32	410
12.6	5.41	21.64	32.00	10.36	25.90	.209	8,070	32	410
13.4	5.13	20.52	36.00	15.48	38.70	.1325	7,600	27	390

[a]Rheological data taken from ref. 2.
[b]Rheological data taken from ref. 3.

TABLE IV. - COMPARISON OF CALCULATED SPECIFIC SURFACES AND EQUIVALENT DIAMETERS

	Magnesium			
	C	D	FP-1	FP-3
Known or estimated from observation: Particle diameter, microns[a]	1.5 (average)	Largely <0.7	Largely 0.06 to 0.2	Largely <0.2
Calculated from slope of Langmuir plot: Specific surface, sq m/g	2.8	7.8	-----	---
Average particle diameter, microns	1.2	0.44	-----	---
Calculated from minimum Brookfield viscosity and yield value: Specific surface, sq m/g	3.0	5.4	20	7.9 to 11
Average particle diameter, microns	1.1	0.63	0.17	0.30 to 0.42

[a]For details of measurements, see table I.

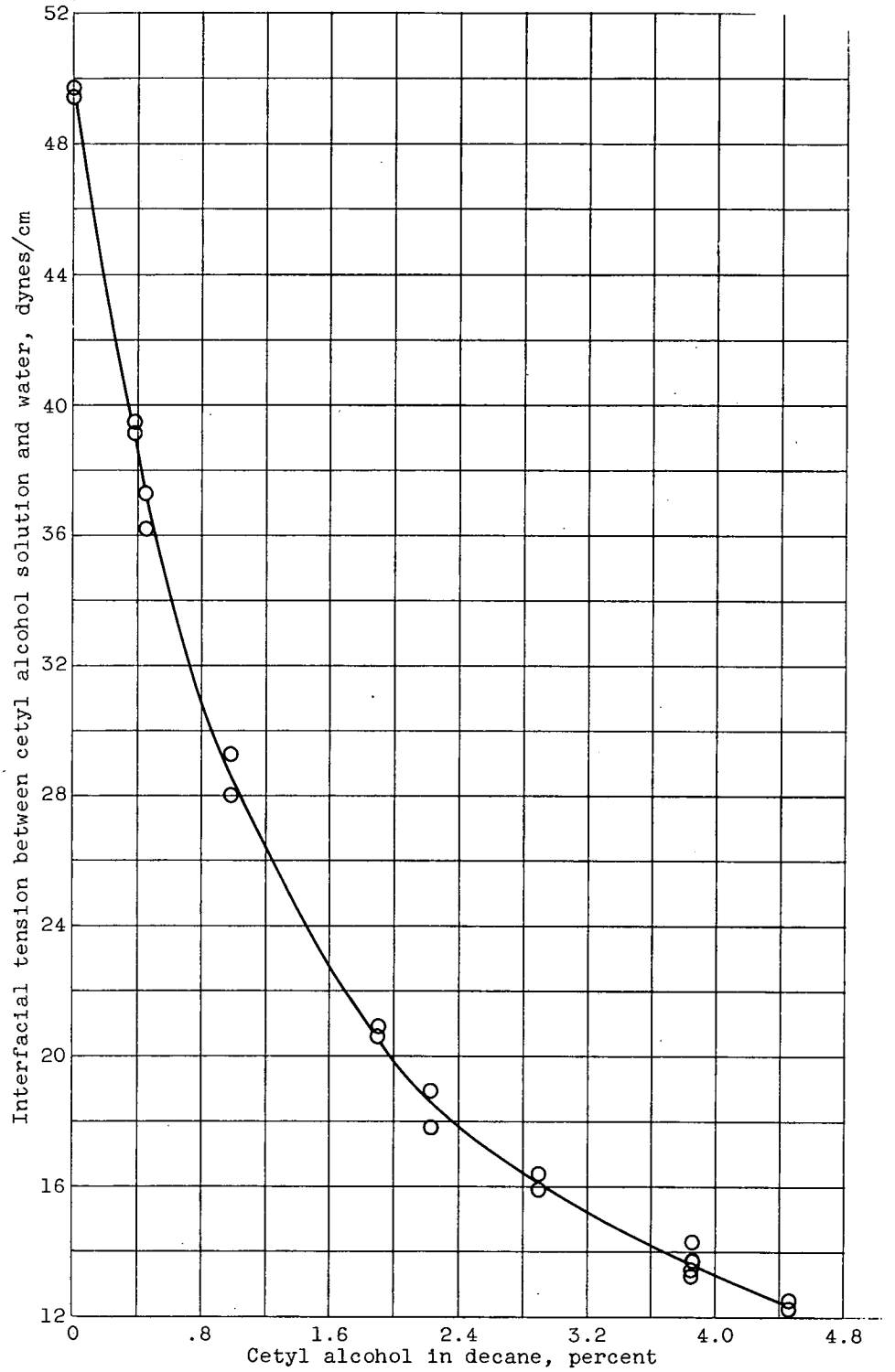
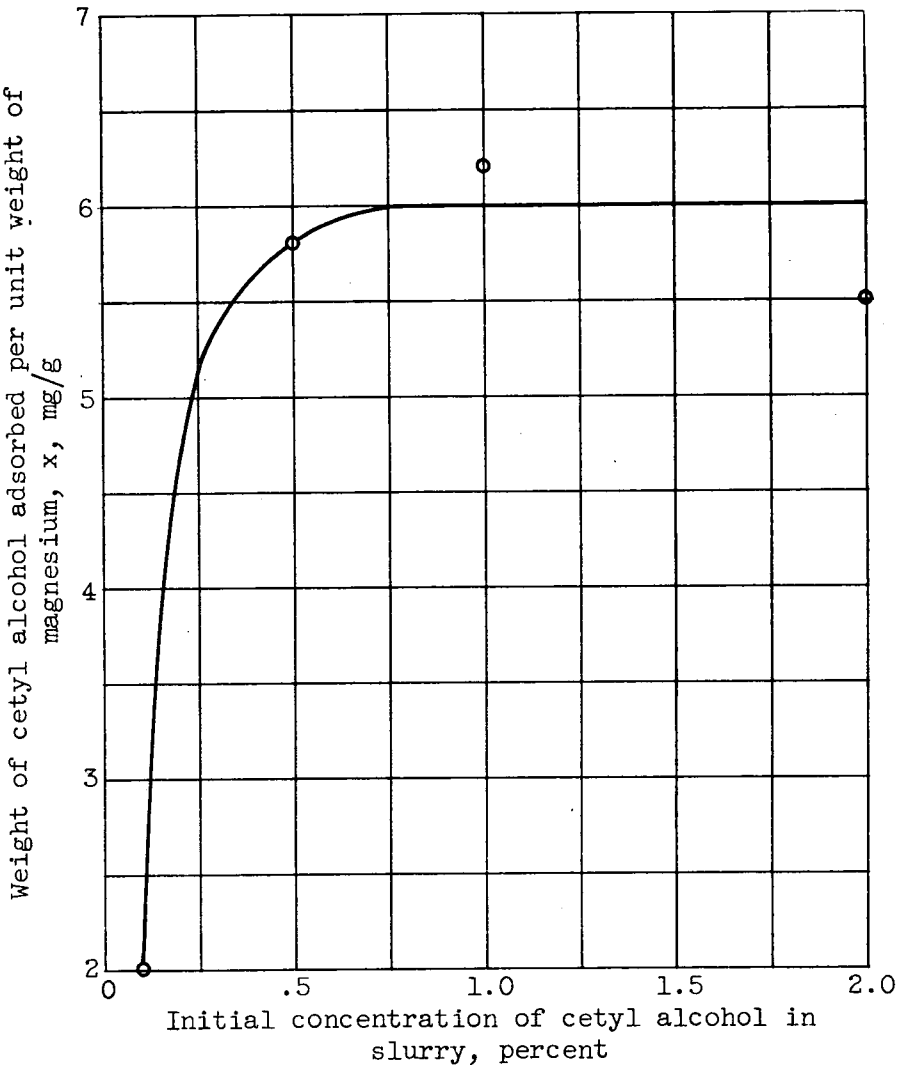
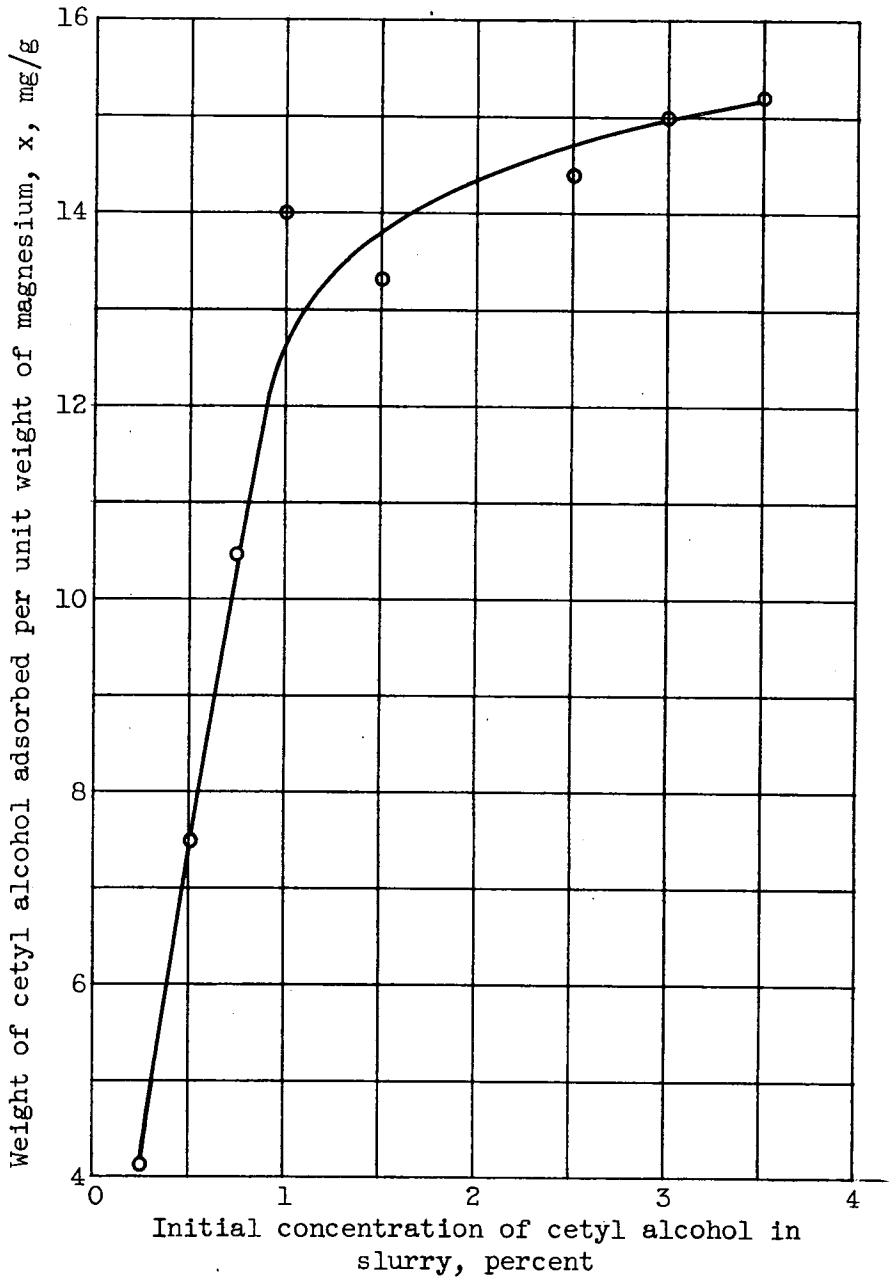


Figure 1. - Calibration curve for determination of cetyl alcohol concentration in decane from interfacial tension between solution and water.



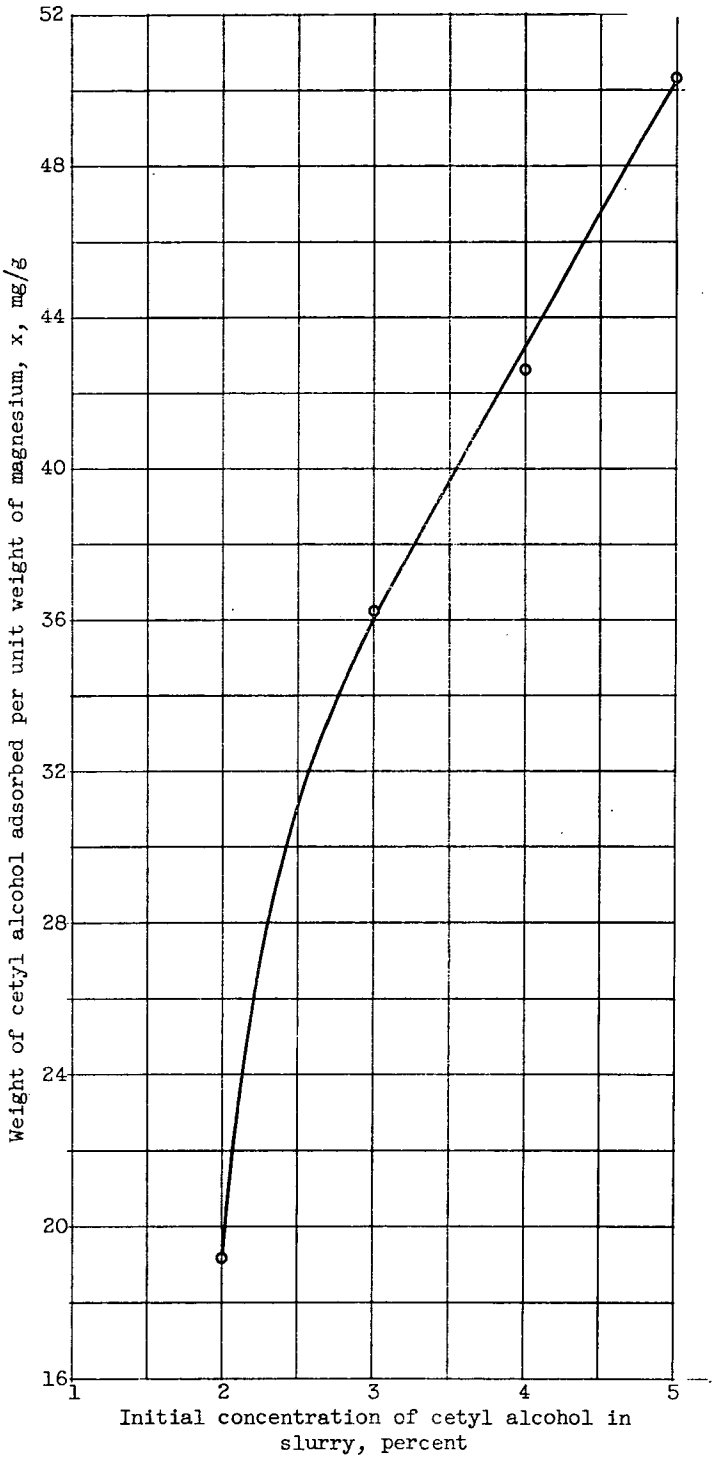
(a) Magnesium C in decane. Slurry centrifuged at 1750 rpm.

Figure 2. - Adsorption of cetyl alcohol from hydrocarbon solution by magnesium at room temperature.



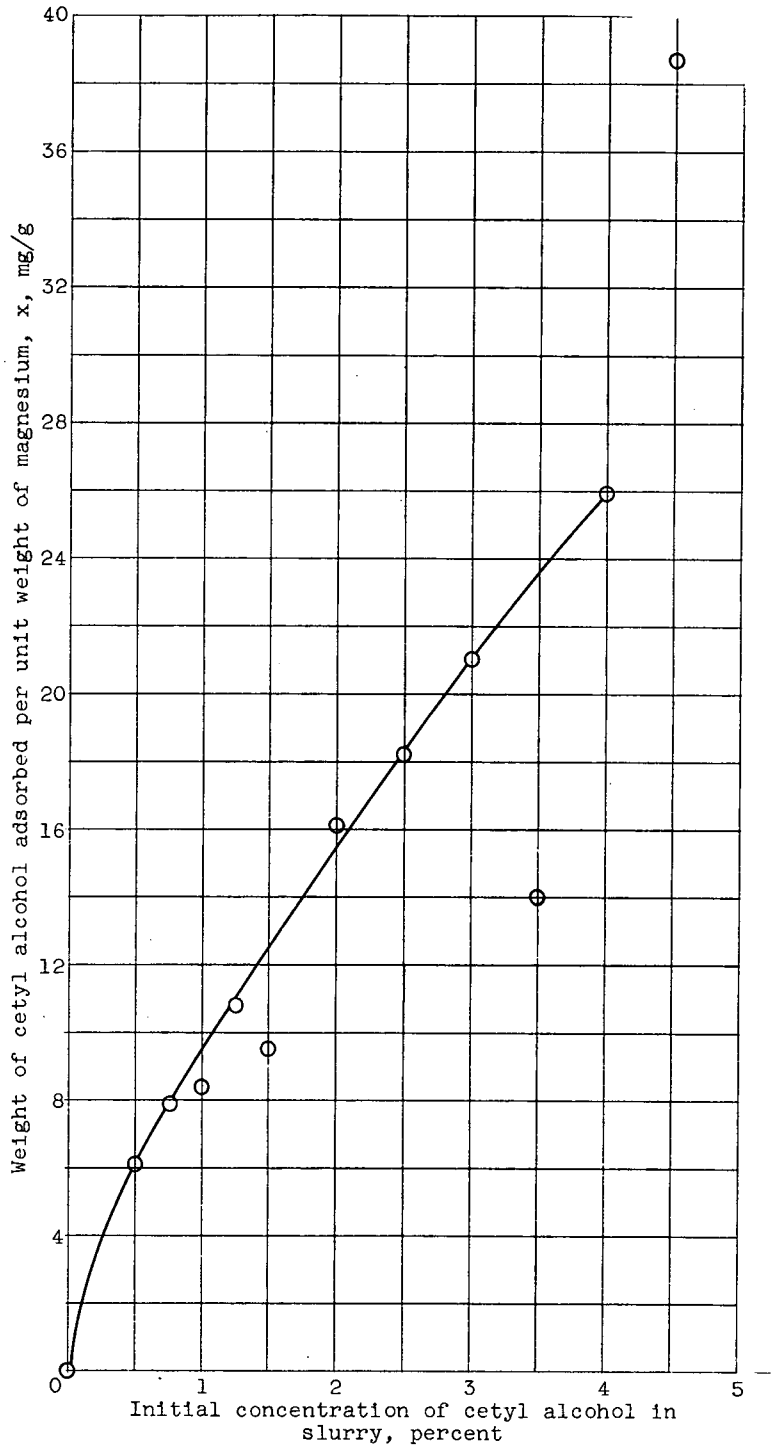
(b) Magnesium D in decane. Slurry centrifuged at 1750 rpm.

Figure 2. - Continued. Adsorption of cetyl alcohol from hydrocarbon solution by magnesium at room temperature.



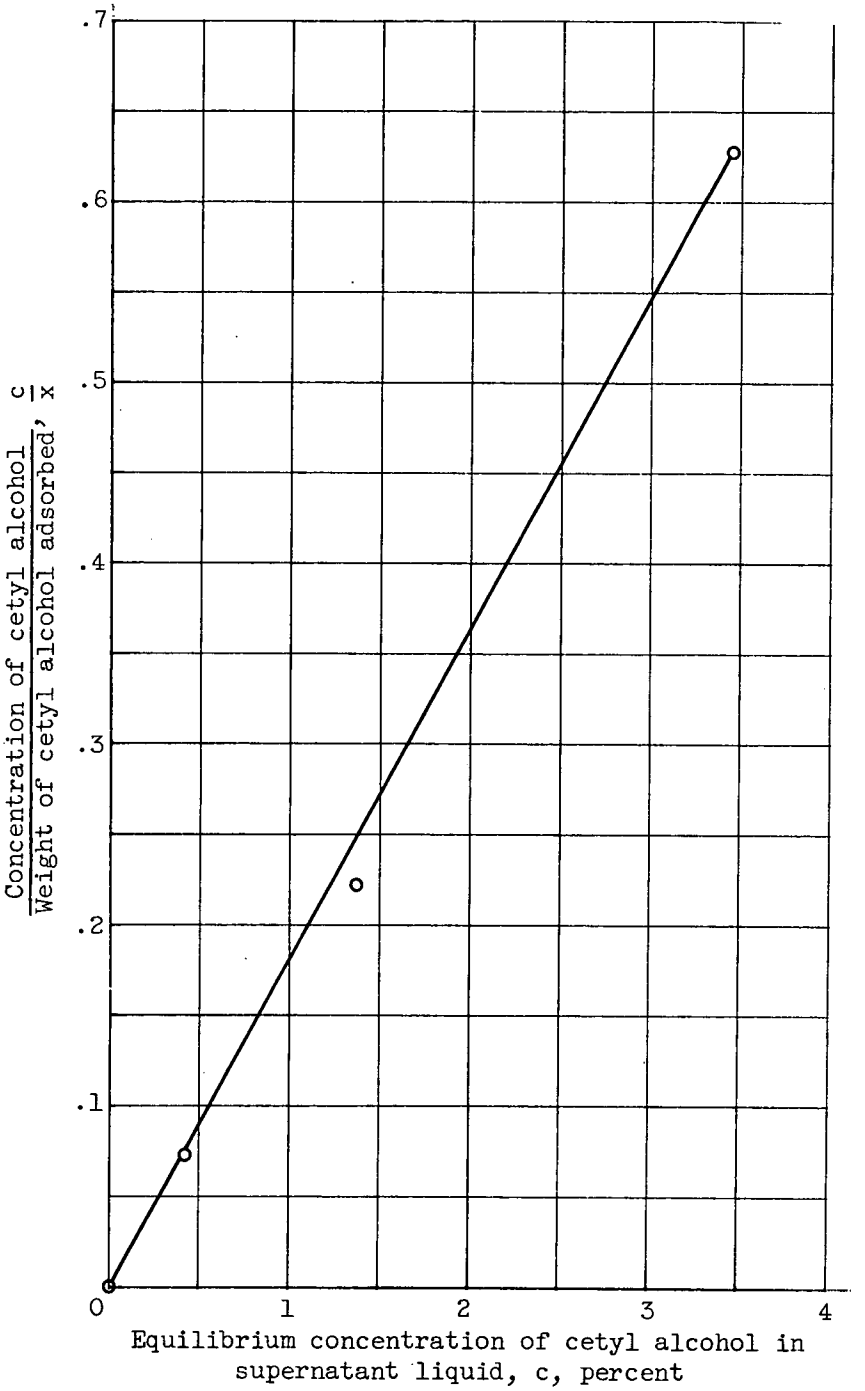
(c) Magnesium FP-1 in JP-1 fuel. Supernatant liquid centrifuged at 29,000 rpm.

Figure 2. - Continued. Adsorption of cetyl alcohol from hydrocarbon solution at room temperature.



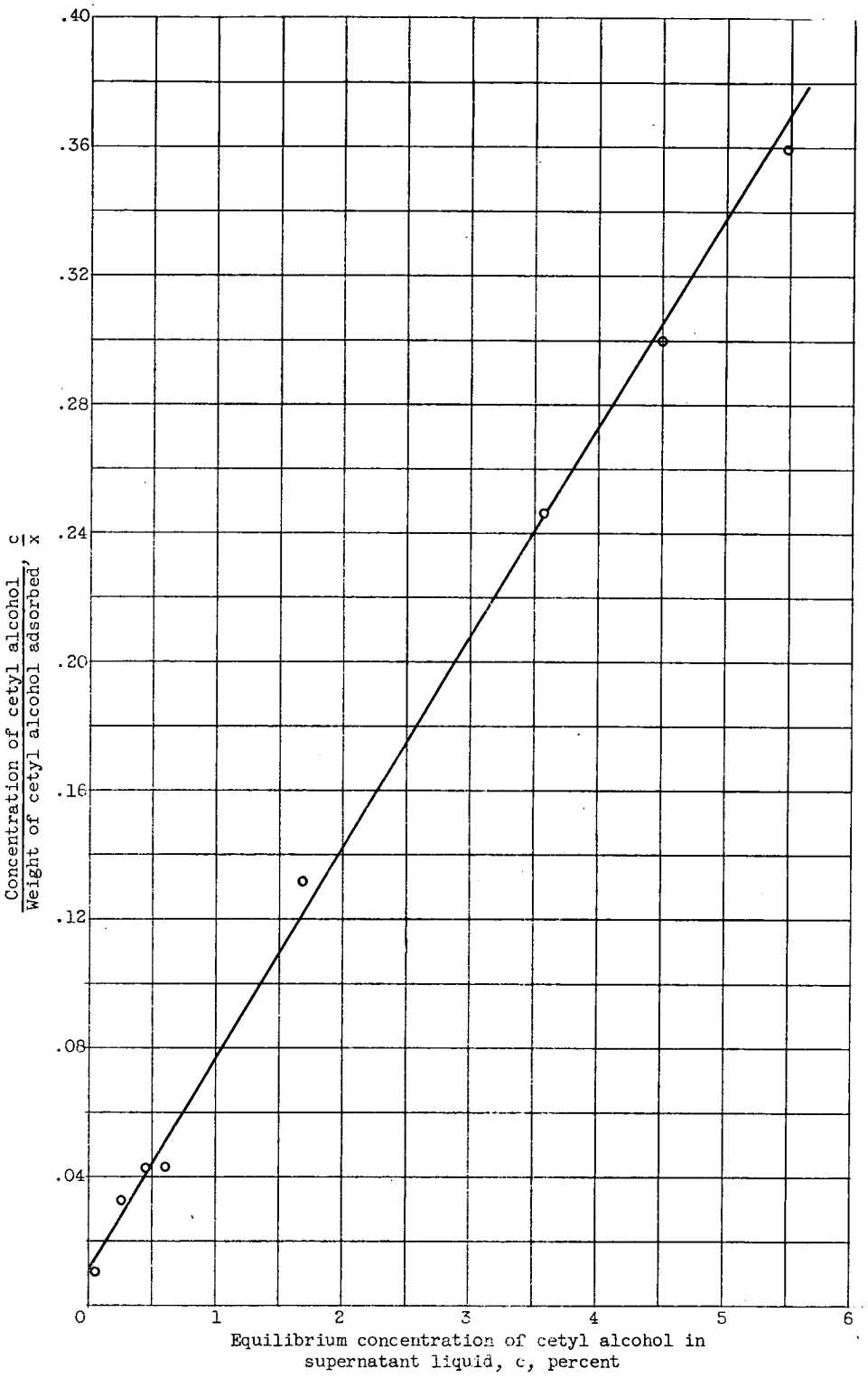
(d) Magnesium FP-3 in JP-5 fuel. Slurry centrifuged at 1750 rpm.

Figure 2. - Concluded. Adsorption of cetyl alcohol from hydrocarbon solution by magnesium at room temperature.



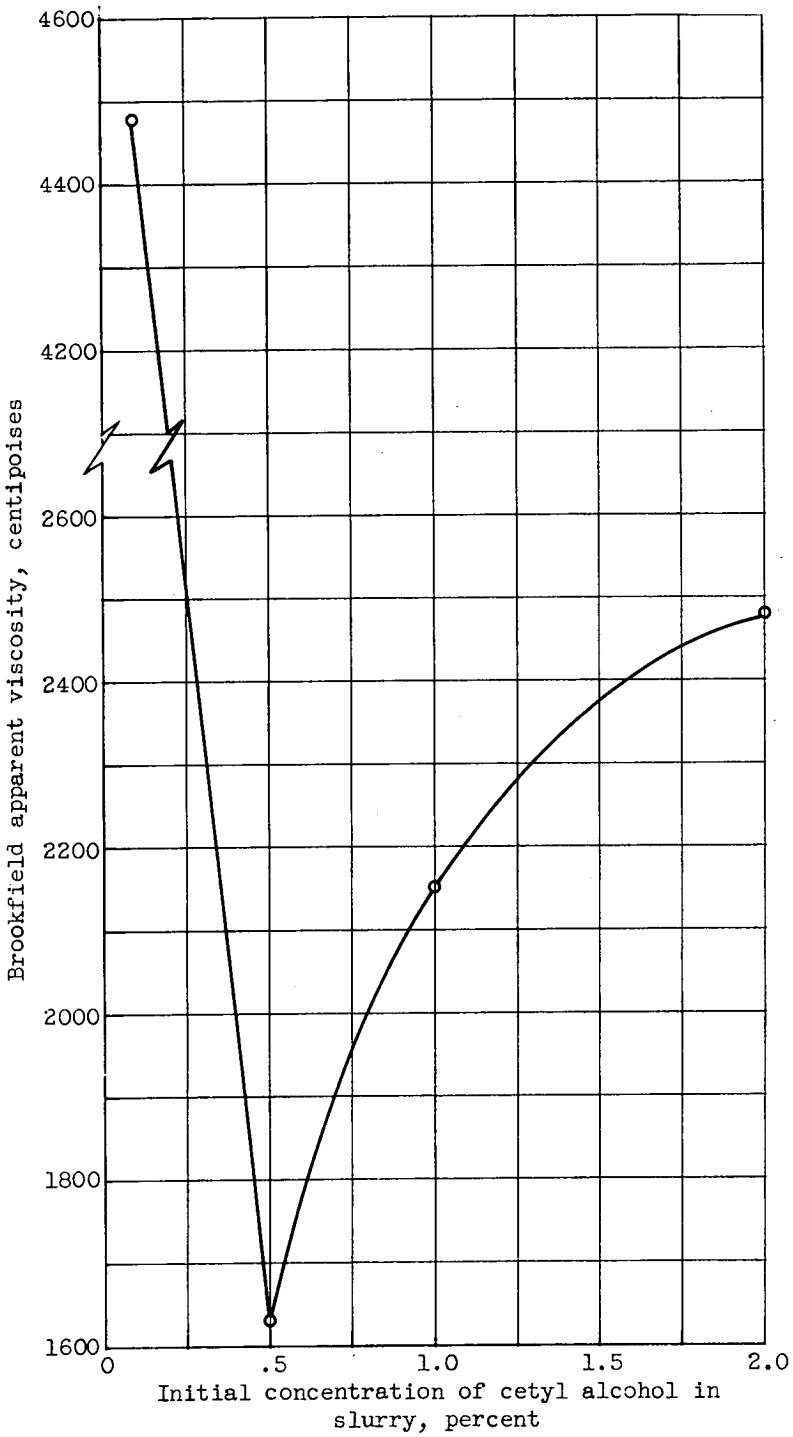
(a) Magnesium C in decane. Slurry centrifuged at 1750 rpm.

Figure 3. - Langmuir plot for adsorption of cetyl alcohol from hydrocarbon solution at room temperature.



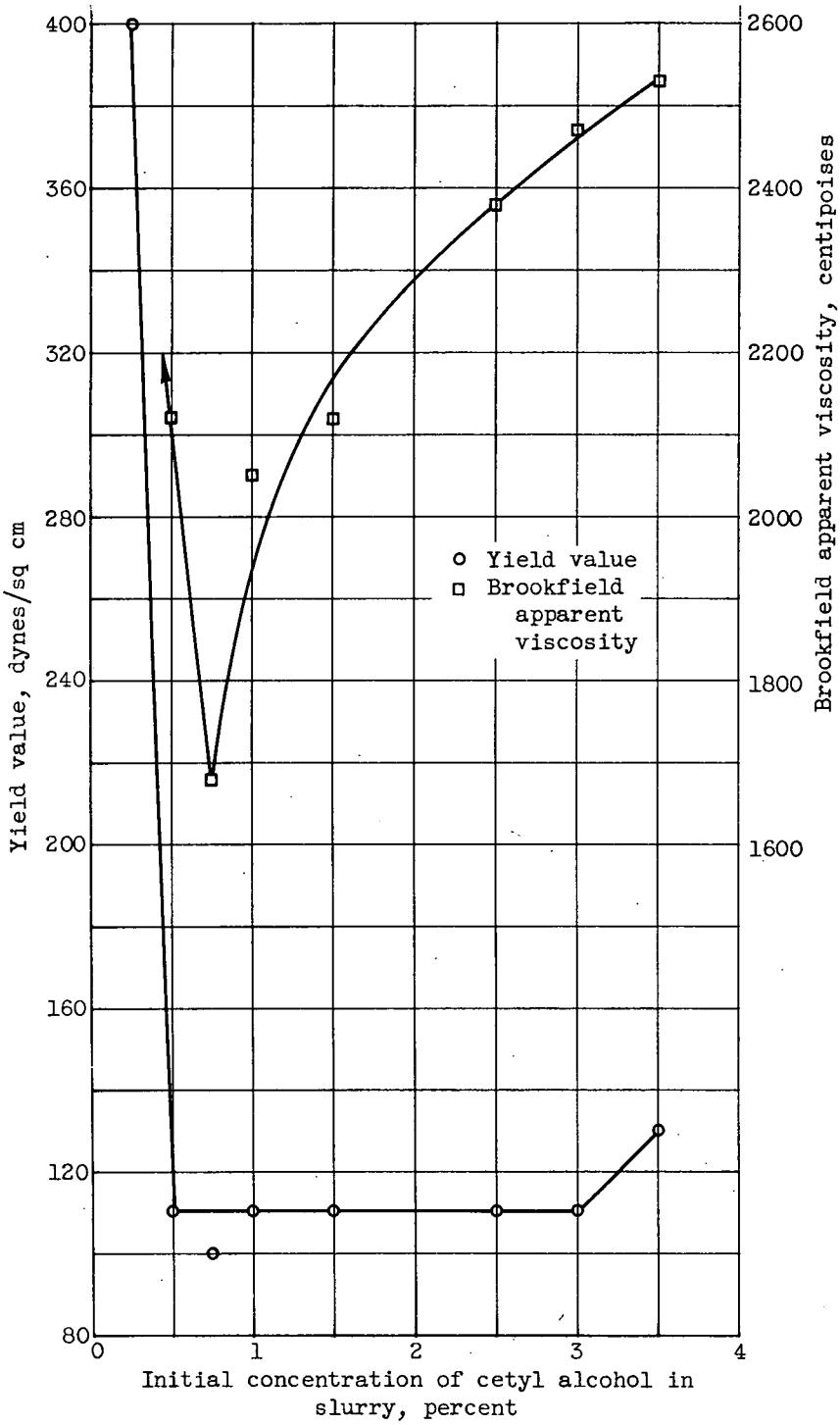
(b) Magnesium D in decane. Slurry centrifuged at 1750 rpm.

Figure 3. - Concluded. Langmuir plot for adsorption of cetyl alcohol from hydrocarbon solution by magnesium at room temperature.



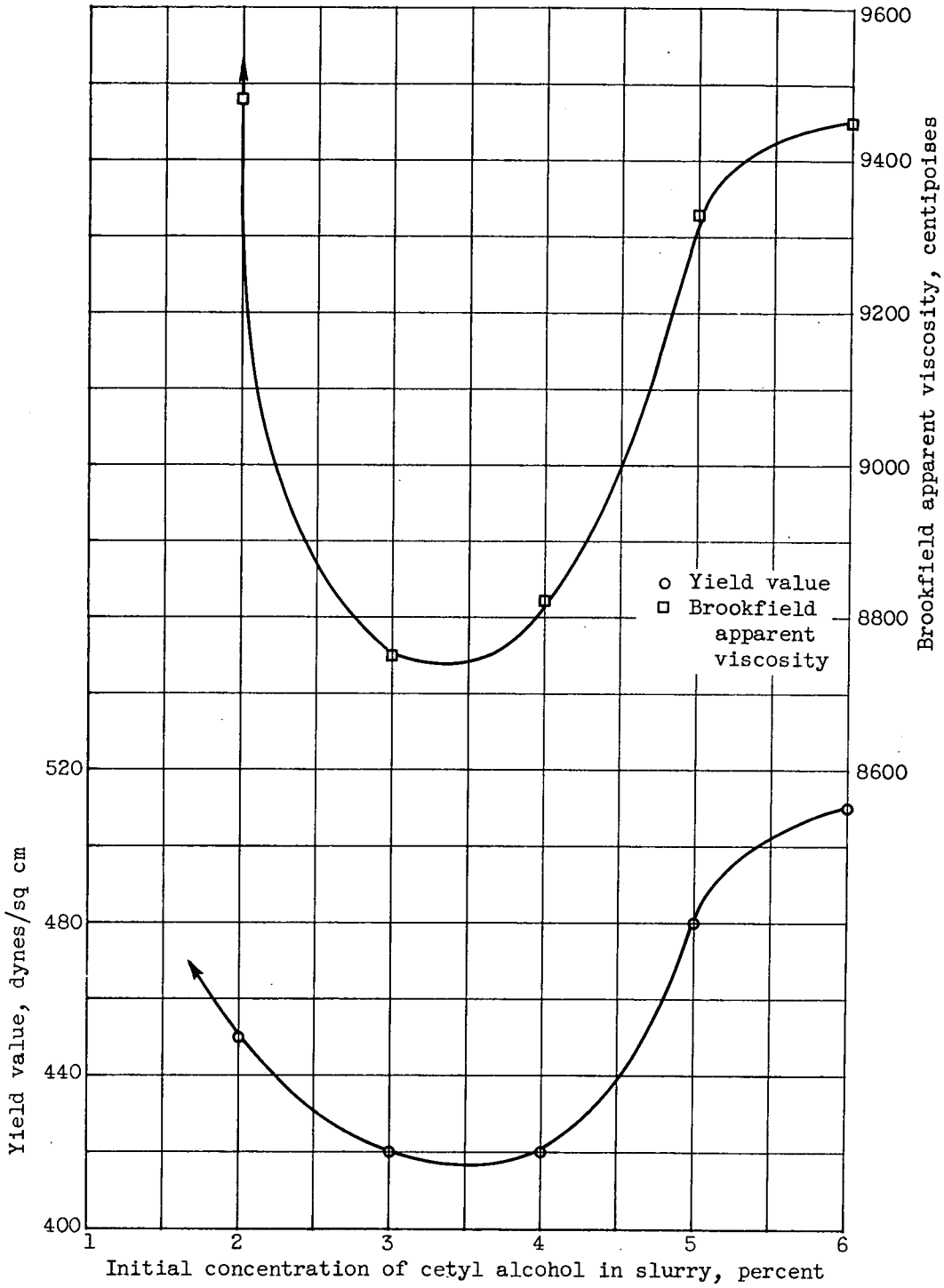
(a) Magnesium C in decane.

Figure 4. - Brookfield apparent viscosities and yield values of magnesium slurries containing cetyl alcohol.



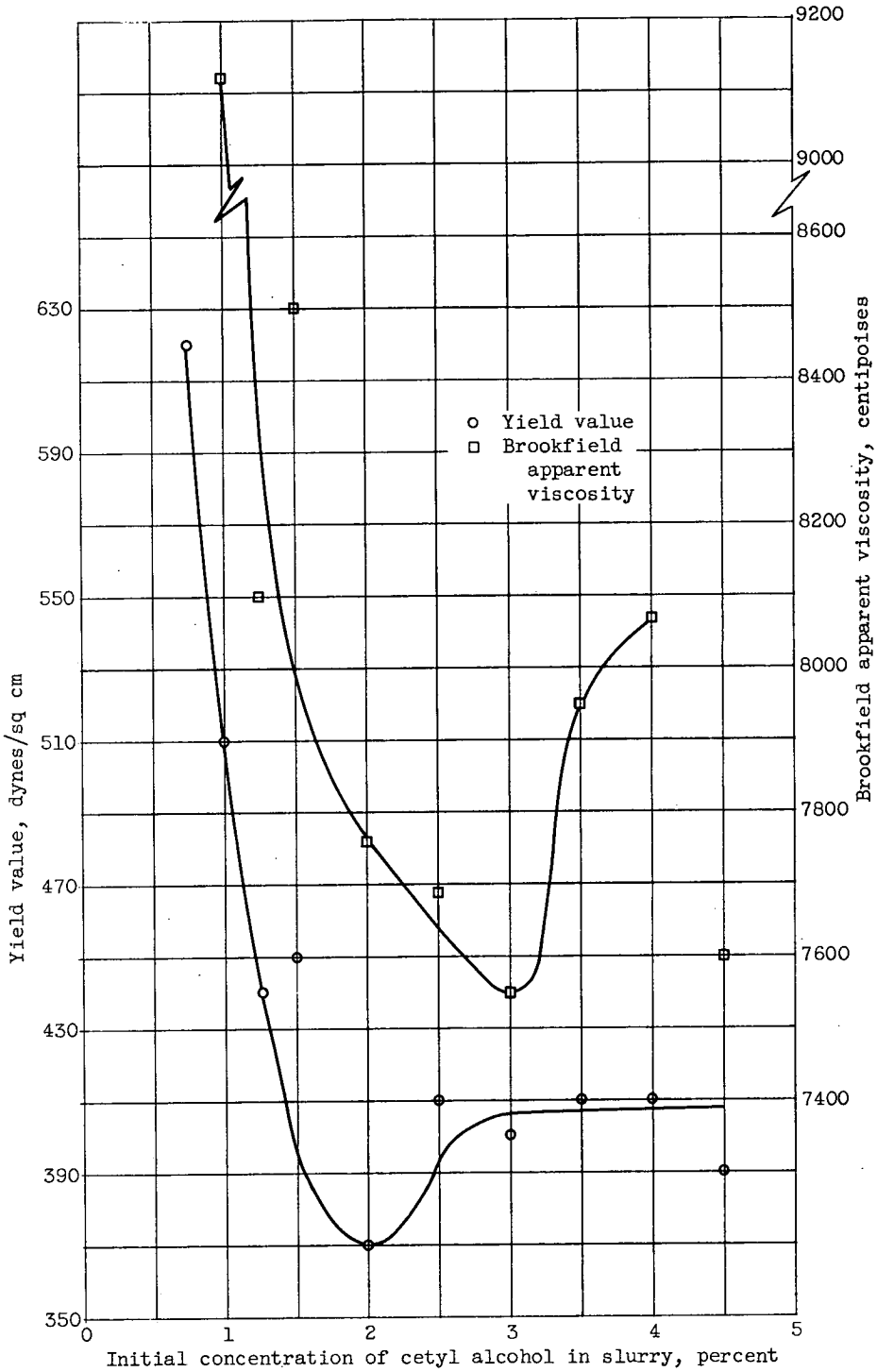
(b) Magnesium D in decane.

Figure 4. - Continued. Brookfield apparent viscosities and yield values of magnesium slurries containing cetyl alcohol.



(c) Magnesium FP-1 in JP-1 fuel.

Figure 4. - Continued. Brookfield apparent viscosities and yield values of magnesium slurries containing cetyl alcohol.



(d) Magnesium FP-3 in JP-5 fuel plus 10 percent fuel oil.

Figure 4. - Concluded. Brookfield apparent viscosities and yield values of magnesium slurries containing cetyl alcohol.